

*Final Report
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Final Report

**Radiometric Calibration of the Earth
Observing System's Imaging Sensors**

NASA Grant NAGW-896

Submitted by :

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Introduction

This is the final report on grant No. NAGW-896, titled “Radiometric Calibration of the Earth Observing System’s Imaging Sensors.” The work on the grant was mainly directed towards developing new, accurate, redundant methods for the in-flight, absolute radiometric calibration of satellite multispectral imaging systems and refining the accuracy of methods already in use. Initially the work was in preparation for the calibration of MODIS and HIRIS (before the development of that sensor was canceled), with the realization it would be applicable to most imaging multi- or hyper-spectral sensors provided their spatial or spectral resolutions were not too coarse.

The work on the grant involved three different ground-based, in-flight calibration methods:

- reflectance-based

- radiance-based

- and diffuse-to-global irradiance ratio used with the reflectance-based method.

This continuing research had the dual advantage of 1) developing several independent methods to create the redundancy that is essential for the identification and hopefully the elimination of systematic errors, and 2) refining the measurement techniques and algorithms that can be used not only for improving calibration accuracy but also for the reverse process of retrieving ground reflectances from calibrated remote-sensing data.

The grant also provided the support necessary for us to embark on other projects such as the ratioing radiometer approach to on-board calibration (this has been further developed by SBRS as the “solar diffuser stability monitor” and is incorporated into the most important on-board calibration system for MODIS); another example of the work, which was a spin-off from the grant funding, was a study of solar diffuser materials. Finally the grant provided funding for equipment needed by graduate students in their research activities; many of our students benefited from NASA fellowships, but these fellowships did not provide capital equipment money.

Instead of writing a narrative account of the research conducted under the grant I have chosen to list the publications authored by faculty, staff and students supported by the grant together with journal citations, titles and abstracts, and Ph.D. dissertations and M.S. theses supported by the grant together with their abstracts. I believe this will provide the reader with a concise review of all the work performed and the information necessary for her/him to dig deeper. This is followed by a few concluding remarks and acknowledgments to those who have supported us, the Remote Sensing Group (RSG), including the many scientific collaborators we have been associated with during the past several years.

Publications authored by faculty, staff and students supported by the grant

"Vicarious Radiometric Calibrations of EOS Sensors,"

Slater, P.N., S.F. Biggar, K.J. Thome, D.I. Gellman, and P.R. Spyak,
Journal of Atmospheric and Oceanic Technology 13:2:349-359, April 1996.

Abstract:

Four methods for the in-flight radiometric calibration and cross calibration of multispectral imaging sensors are described. Three make use of ground-based reflectance, irradiance, and radiance measurements in conjunction with atmospheric measurements and one compares calibrations between sensors.

Error budgets for these methods are presented and their validation is discussed by reference to SPOT and TM results and shown to meet the EOS requirements in the solar-reflective range.

"Radiometric calibration of ASTER data,"

Slater, P.N., K. J. Thome, K. Arai, H. Fujisada, H.H. Kieffer, A. Ono, F. Sakuma,
F.D. Palluconi, and Y. Yamaguchi,
Journal of Remote Sensing of Japan, Special issue on ASTER, 15:16-23, 1995.

Abstract:

Preflight and in-flight radiometric calibration plans are described for the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER), which is a high spatial resolution imaging spectroradiometer. It is designed for the remote sensing from orbit of land, lakes, coastal and ocean surfaces, and clouds, and is expected to be launched in 1998 on NASA's EOS AM-1 Spacecraft. ASTER comprises three subsystems which acquire images in three separate spectral regions: the visible and near infrared (VNIR), the shortwave infrared (SWIR), and the thermal infrared (TIR). The absolute radiometric accuracy is required to be better than 4% for VNIR and SWIR radiance measurements, and 1K to 3K, depending on the temperature region from 200K to 370K, for TIR temperature measurements.

"Calibration and performance evaluation of a portable shortwave infrared (1.05- to 2.45- μm) spectrometer,"

Smith, M.W. and S. F. Biggar,
Optical Engineering 33:11:3781-3792, November 1994.

Abstract:

A portable shortwave infrared (SWIR) spectrometer has been developed that covers the range from 1.05 to 2.45 μm . The spectral sampling interval is 1.37 nm, and the spectral resolution can be varied from about 5 nm to more than 100 nm. A single spectrum can be acquired in as little as 1 s. The signal-to-noise ratio (SNR) for a single 1-s scan is about 100 at a wavelength of 2.2 μm for a lambertian surface of 100% reflectance illuminated by the sun at normal incidence with 14-nm spectral resolution. The SNR at 1.25 μm is about 900 for the same conditions. The estimated 1σ

uncertainty in the absolute radiometric calibration of the instrument is 2% to 3%. Field-of-view defining optics are coupled by a flexible fiber optic bundle to the spectrometer, which consists of a non-scanning concave holographic diffraction grating with a flat focal field imaged onto a 1024-element liquid nitrogen cooled PtSi linear array detector. The primary use for the instrument is the collection of ground reflectance and radiance data for the radiometric calibration of operational and proposed high spectral resolution remote sensing systems.

"The in-flight radiometric calibration of ASTER by reference to well-characterized scenes,"

Slater, P.N., S. F. Biggar, K.J. Thome, D.I. Gellman and P.R. Spyak,
SPIE Proceedings, Platforms and Systems, Vol. 2317:49-60, 1994.

Abstract:

ASTER will be calibrated in the laboratory by reference to sources traceable to NRLM and NIST standards and through the use of transfer radiometers. Partial aperture on-board calibration systems will be used in the solar-reflective range and an on-board blackbody source will be used in the infrared. An important independent source of calibration data will be provided through the in-flight radiometric calibration of ASTER by reference to well-characterized scenes. The latter is the subject of this paper.

Methods that make use of ground reflectance and radiance measurements made simultaneously with atmospheric measurements at selected sites and used as input to radiative transfer codes will be described. The results of error analyses will be presented indicating that, depending on the method used, the predicted uncertainties fall between $\pm 2.8\%$ and $\pm 4.9\%$, for the solar-reflective range. In the thermal infrared, the goal is an uncertainty of less than 1K.

A method that provides in-flight cross calibrations with other sensors will also be described.

"Three-channel solar radiometer for the determination of atmospheric columnar water vapor,"

Thome, K.J., M.W. Smith, J.M. Palmer and J.A. Reagan,
Applied Optics, 33:24:5811-5819, August 20, 1994.

Abstract:

The design of a three-channel solar radiometer used to determine total columnar atmospheric water-vapor amounts is presented. The main channel is located in the 0.94- μm water-vapor band, and two other channels are located in adjacent nonabsorption regions of the solar spectrum and are used to remove scattering effects from the main channel. Water-vapor transmittance is determined by means of a modified Langley approach, and these transmittances are converted to columnar water vapor by means of a band model developed at the University of Arizona. Several cases are presented in which columnar water-vapor amounts are determined through the use of the instrument and method described here. These results are compared with sounding-balloon results. Tests of the method indicate that columnar water vapor may be retrieved with an uncertainty of less than 10%.

"Uncertainties in the in-flight calibration of sensors with reference to measured ground sites in the 0.4-1.1 μm range,"

Biggar S.F., P.N. Slater and D.I. Gellman,
Remote Sens. Environ. 48:245-252, 1994.

Abstract:

This article describes the error sources for three in-flight sensor calibration methods used by the Remote Sensing Group of the Optical Sciences Center at the University of Arizona. The three methods are the reflectance-, improved reflectance-, and radiance-based methods, which all reference the earth-atmosphere system. The sources of error or uncertainty for each method are discussed, and an estimate of the percent uncertainty associated with each source is made for conditions similar to those actually used for calibrations at White Sands, New Mexico. The results of in-flight calibrations are compared to those of the on-board lamp calibration system for a SPOT HRV camera.

"Method and instrument for retrieving total columnar water vapor from solar transmittance,"

Thome, K.J., M.W. Smith, J.M. Palmer, and J.A. Reagan,
SPIE Proceedings, 1968:56:526-532, April, 1993.

Abstract:

The design of a three-channel solar radiometer for obtaining total columnar water vapor using solar transmittance and differential absorption is presented. Water vapor transmittance is determined using a modified Langley approach and converted to columnar water vapor using a band model developed at the University of Arizona. Several cases are presented in which columnar water vapor amounts determined using the current instrument and method are compared to sounding balloon results. Tests using simulated data indicate that columnar water vapor may be retrieved with an uncertainty less than 10%.

"Design and initial performance evaluation of a portable short wave infrared spectroradiometer,"

Smith, Mark W.,
SPIE Proceedings 1762:14:118-134, July 1992.

Abstract:

The design, initial calibration, and performance evaluations of a portable short wave infrared (SWIR) spectroradiometer are described. The spectroradiometer covers the range from 1.1 to 2.5 μm with a spectral resolution that may be varied from less than 10 nm to more than 100 nm. A single spectrum is acquired in about 2 seconds. The signal-to-noise ratio (SNR) is about 230 at a wavelength of 2.2 μm for a lambertian surface of 90% reflectance illuminated by the sun at normal incidence with 14.8 nm resolution, a 25° C background temperature, and no atmospheric attenuation. Field-of-view defining optics are coupled by a flexible fiber-optics bundle to the spectroradiometer, which consists of a concave holographic diffraction grating with a flat focal field imaged onto a 1024-element platinum silicide linear-array detector.

"Results of calibrations of the NOAA-11 AVHRR made by reference to calibrated SPOT imagery at White Sands, N.M.,"

Nianzeng, C., B.G. Grant, D.E. Flittner, P.N. Slater, S.F. Biggar, R.D. Jackson, and M.S. Moran,

SPIE Proceedings, 1493:21:182-194, April 1991.

Abstract:

The calibration method reported here makes use of the reflectances of several large, uniform areas determined from calibrated and atmospherically corrected SPOT Haute Resolution Visible (HRV) scenes of White Sands, New Mexico. These reflectances were used to predict the radiances in the first two channels of the NOAA-11 Advanced Very High Resolution Radiometer (AVHRR). The digital counts in the AVHRR image corresponding to these known reflectance areas were determined by the use of two image registration techniques. The plots of digital counts versus pixel radiance provided the calibration gains and offsets for the AVHRR. A reduction in the gains of 4% and 13% in channels 1 and 2 respectively was found during the period 1988-11-19 to 1990-6-21.

An error budget is presented for the method and is extended to the case of cross-calibrating sensors on the same orbital platform in the Earth Observing System (Eos) era.

"Stability of narrow-band filter radiometers in the solar-reflective range,"

Flittner, D.E. and P.N. Slater,

Photogrammetric Engineering & Remote Sensing, 57:2:165-171, February 1991.

Abstract:

We show that the calibration, with respect to a continuous-spectrum source, and the stability of radiometers using filters of about 10 nm full width, half maximum (FWHM) in the wavelength interval 0.4 to 1.0 μm , can change by several percent if the filters change in position by only a few nanometers. The cause is the shifts of the passbands of the filters into or out of Fraunhofer lines in the solar spectrum or water vapor or oxygen absorption bands in the Earth's atmosphere. These shifts can be due to ageing accompanied by the absorption of water vapor into the filter or temperature changes for field radiometers, or to outgassing and possibly high energy solar irradiation for space instruments such as the MODerate resolution Imaging Spectrometer - Nadir (MODIS-N) proposed for the Earth Observing System.

"The in-flight calibration of a helicopter-mounted Daedalus multispectral scanner,"

Balick, L.K., C.J. Golanics, J.E. Shines, S.F. Biggar and P.N. Slater,

SPIE Proceedings, Vol 1943-24, 1991.

Abstract:

A convenient way that has been used to calibrate, in-flight, a helicopter-mounted Daedalus multispectral scanner is described. It used four large canvas panels laid out in a square with a Spectralon panel as a reference. A calibrated Barnes modular multispectral radiometer, carried on a 2.2-m boom was rotated around a 2.5-m high tripod at the center of the square. The radiometer sampled for four large panels and the Spectralon panel once every two minutes. Atmospheric spectral transmittance measurements were made using a filter radiometer on an autotracking mount during

the morning of the flight. The reflectance and optical depth data were used in an atmospheric radiative transfer code to predict the spectral radiances at the scanner. The calibration was completed by comparing the image digital counts to the predicted spectral radiances.

"Radiometric calibration of SPOT 2 HRV - A comparison of three methods,"

S.F. Biggar, M.C. Dinguirard, D.I. Gellman, P. Henry, R.D. Jackson, M.S. Moran and P.N. Slater,

SPIE Proceedings, Vol. 1943-17, 1991.

Abstract:

Three methods for determining an absolute radiometric calibration of a spacecraft optical sensor are compared. They are the well-known reflectance-based and radiance-based methods, and a new method based on measurements of the ratio of diffuse-to-global irradiance at the ground. The latter will be described in detail and the comparison of the three approaches will be made with reference to the SPOT-2 HRV cameras for a field campaign 1990-06-19 through 1990-06-24 at the White Sands Missile Range in New Mexico.

"Improved evaluation of optical depth components from Langley plot data,"

Biggar, S.F., D.I. Gellman and P.N. Slater,

Remote Sens. Environ. 32:91-101, 1990.

Abstract:

A simple, iterative procedure to determine the optical depth components of the extinction optical depth measured by a solar radiometer is presented. Simulated data show that the iterative procedure improves the determination of the exponent of a Junge Law particle size distribution. The determination of the optical depth due to aerosol scattering is improved as compared to a method which uses only two points from the extinction data. The iterative method was used to determine spectral optical depth components for 11-13 June 1988 during the MAC III experiment.

"Surface reflectance factor retrieval from Thematic Mapper data,"

Holm, R.G., R.D. Jackson, B.Yuan, M.S. Moran, P.N. Slater, and S.F. Biggar,
Remote Sens. Environ. 27:47-57, 1989.

Abstract:

Based on the absolute radiometric calibration of the Thematic Mapper (TM) and the use of a radiative transfer program for atmospheric correction, ground reflectances were retrieved for several fields of crops and bare soil in TM Bands 1-4 for six TM scenes acquired over a 12-month period. These reflectances were compared to those measured using ground-based and low-altitude, aircraft-mounted radiometers. When, for four TM acquisitions, the comparison was made between areas that had been carefully selected for their high uniformity, the reflectance factors agreed to ± 0.01 (1σ RMS) over the reflectance range 0.02-0.55. When the comparison was made for two of the above acquisitions and two others on different dates, for larger areas not carefully selected to be of uniform reflectance, the reflectance factors agreed to ± 0.02 (1σ RMS), again over the reflectance range 0.02-0.55.

"Absolute radiometric calibration of the NOAA AVHRR sensors,"

Teillet, P.M., P.N. Slater, Y. Mao, Y. Ding, B. Yuan, R.J. Bartell, S.F. Biggar, R.P. Santer, R.D. Jackson and M.S. Moran,
SPIE Proceedings, Vol. 924, 1988.

Abstract:

Three different approaches are described for the absolute radiometric calibration of the two reflective channels of the NOAA AVHRR sensors. Method 1 relies on field measurements and refers to another calibrated satellite that acquired high-resolution imagery on the same day as the AVHRR overpass. Method 2 makes no reference to another sensor and is essentially an extension of the reflectance-based calibration method developed at White Sands for the in-orbit calibration of Landsat TM and SPOT HRV data. Method 3 achieves a calibration by reference to another satellite sensor, but it differs significantly from the first approach in that no ground reflectance and atmospheric measurements are needed on overpass day. Calibration results have been obtained using these methods for four NOAA-9 AVHRR images and for one NOAA-10 AVHRR image. A significant degradation in NOAA-9 AVHRR responsivity has occurred since the prelaunch calibration and with time since launch. The responsivity of the NOAA-10 AVHRR has also degraded significantly compared to the prelaunch calibration. The suitabilities of using Method 2 with the Rogers Dry Lake site in California and using Methods 1 and 3 at White Sands are discussed.

The results for Method 3, which requires no field measurements and makes use of a simplified atmospheric model, are very promising, implying that a reasonable calibration of satellite sensors may be relatively straightforward.

"Laboratory calibration of field reflectance panels,"

Biggar, S.F., J. Labed, R.P. Santer, P.N. Slater, R.D. Jackson, M.S. Moran,
SPIE Proceedings, Vol 924, 1988.

Abstract:

A method used for calibrating field reflectance panels in the visible and shortwave infrared wavelength range is described. The directional reflectance factor of painted barium sulfate (BaSO_4) panels is determined.

The reference for this method is the hemispherical reflectance of pressed polytetrafluorethylene (halon) powder prepared according to National Bureau of Standards (NBS) directions. The panels and a radiometer are mounted on rotation stages to measure the reflectance factor at different incidence and view angles. The sensor can be any laboratory or field filter radiometer small enough to mount on the apparatus.

The method is used to measure the reflectance factors of halon and BaSO_4 panels between 0.45 and 0.85 micrometers. These reflectance factors are compared to those measured by a field apparatus. The results agree to within 0.013 in reflectance at incidence angles between 15 and 75 degrees.

"Review of the calibration of radiometric measurements from satellite to ground level,"

Slater, P.N.,

Proceedings International Society of Photogrammetry and Remote Sensing, 1988.

Abstract:

This review discusses satellite sensor spectroradiometric calibration and mentions specific advantages and disadvantages of some of the commonly used methods. The importance of the use of several independent methods is stressed. Ground-based measurements and results are described for a reflectance-based, in-flight, sensor calibration method. Results are also presented for the reverse process, i.e. for retrieving ground reflectance from calibrated sensor data. Finally the magnitude of uncertainties in the ground and atmospheric measurements associated with the reflectance-based method and their combined effect on the uncertainty of the final in-flight calibration are estimated.

"Radiometric calibration requirements and atmospheric correction."

Slater, P.N.,

SPIE Proceedings, Vol. 924, 144-150, 1988.

Abstract:

The need for independent, redundant absolute radiometric calibration methods is discussed with reference to the Thematic Mapper. Uncertainty requirements for absolute calibration of between 0.5% and 4% are defined based on the accuracy of reflectance retrievals at an agricultural site. It is shown that even very approximate atmospheric corrections can reduce the error in reflectance retrieval to 0.02 over the reflectance range 0 to 0.4.

Ph.D. dissertations and M.S. theses supported by the grant

Carol Jane Kastner (now Bruegge), 1985 Ph.D. dissertation.

"In-flight absolute radiometric calibration of the Landsat Thematic Mapper"

Abstract:

The in-flight absolute radiometric calibration of the Thematic Mapper (TM) is being conducted using the results of field measurements at White Sands, New Mexico. These measurements are made to characterize the ground and atmosphere at the time the TM is acquiring an image of White Sands. The data are used as input to a radiative transfer code that computes the radiance at the entrance pupil of the TM. The calibration is obtained by comparing the digital counts associated with the TM image of the measured ground site with the radiative transfer code result. The calibrations discussed here are for the first four visible and near-infrared bands of the TM.

In this dissertation the data reduction for the first calibration attempts on January 3, 1983, and July 8, 1984, is discussed. Included are a review of radiative transfer theory and a discussion of model atmospheric parameters as defined for the White Sands area. These model parameters are used to assess the errors associated with the calibration procedure. Each input parameter to the radiative transfer code is varied from its model value in proportion to the uncertainty with which it can be determined. The effects of these uncertainties on the predicted radiances are determined. It is thought that the optical depth components τ_{Ray} , τ_{Mie} , τ_{oz} , and τ_{H_2O} can be measured to within 10%, 2%, 10% and 30%, respectively. For the white gypsum sand, surface reflectance uniformity is on the order of 1.5%, and the overall uncertainty in measured reflectance is about 2%. This is due to an uncertainty in the reflectance factor of the calibration plates. The greatest uncertainty in calibration is attributed to our uncertainty in the aerosol parameters, in particular the imaginary component of refractive index. The cumulative effect of these uncertainties is thought to produce an uncertainty in computed radiance of about 5%.

Kenneth Robert Castle, 1985 Ph.D. dissertation.

"Absolute radiometric calibration of a spectro-polarimeter"

Abstract:

Two identical instruments have been developed for use in the field to make radiometric measurements. They have been described as spectropolarimeters because of their ability to make polarization measurements in narrow spectral passbands. They have been used as part of a NASA sponsored project to monitor the spectral and temporal response of the thematic mapper satellites. These satellites allow many natural and man-tended resources to be monitored over years of time, thus allowing their use to be planned for in the future.

The dissertation discusses the design, fabrication, testing and absolute radiometric calibration of these spectropolarimeter instruments. The outstanding feature of these instruments are that they have been calibrated absolutely, for radiance measurements, to an accuracy of $\pm 2\%$ - 3% , in the range of 400 nm to 1040 nm over selected spectral passbands. Previously, field measurements were considered good if they had an absolute accuracy of $\pm 10\%$, implying that the present accuracies are advancing the state-of-the-art for field instrument calibrations. These improved accuracies are the result of using two recently developed calibration standards, both of which use detector based methods. These standards are the Electrically Calibrated Pyroelectric radiometer (ECPR), and the QED-100 quad detector.

The end of the dissertation discusses the attempts made to verify that the accuracies claimed are indeed valid, and it is the author's belief that these accuracies have been verified completely.

Ronald Gene Holm, 1987 Ph.D. dissertation.

"The absolute radiometric calibration of space-based sensors"

Abstract:

The need for absolute radiometric calibration of space-based sensors will continue to increase as new generations of space sensors are developed. A reflectance-based in-flight calibration procedure is used to determine the radiance reaching the entrance pupil of the sensor. This procedure uses ground-based measurements coupled with a radiative transfer code to characterize the effects the atmosphere has on the signal reaching the sensor. The computed radiance is compared to the digital count output of the sensor associated with the image of a test site. This provides an update to the preflight calibration of the system and a check on the on-board internal calibrator.

This calibration procedure was used to perform a series of five calibrations of the Landsat-5 Thematic Mapper (TM). For the 12 measurements made in TM bands 1-3, the RMS variation from the mean as a percentage of the mean is $\pm 1.9\%$, and for measurements in the IR, TM bands 4, 5, and 7, the value is $\pm 2.8\%$.

The absolute calibration techniques were put to another test with a series of three calibrations of the SPOT-1 High Resolution Visible, (HRV), sensors. The ratio, HRV-2/HRV-1, of absolute calibration coefficients compared very well with ratios of histogrammed data obtained when the cameras simultaneously imaged the same ground site. Bands PA, B1 and B3 agreed to within 3%, while band B2 showed a 7% difference.

The procedure for performing a satellite calibration was then used to demonstrate how a calibrated satellite sensor can be used to quantitatively evaluate surface reflectance over a wide range of surface features. Predicted reflectance factors were compared to values obtained from aircraft-based radiometer data. This procedure was applied on four dates with two different surface conditions per date. A strong correlation, $R^2 = .996$, was shown between reflectance values determined from satellite imagery and low-flying aircraft data. Of the 32 predicted reflectance values only six had a difference greater than 0.01. A mean difference of .007 was obtained for the 32 cases. In addition, a procedure had to be developed to obtain uncorrected digital counts from processed satellite imagery.

Richard Joseph Bartell, 1987 M.S. Thesis.

"Atmospheric corrections for in-flight satellite radiometric calibration"

Abstract:

Accurate determination of atmospheric effects is crucial to earth-based in-flight radiometric calibration of existing satellite systems. Such calibration work relies on computer codes which compute atmospheric transmittance due to both scattering and absorption processes.

Two solar radiometers were used for atmospheric data collection. Results obtained from the two instruments in the visible are compared. Modifications to the autotracking instrument are discussed.

The accuracy of existing methods for determining the amounts of key atmospheric constituents actually present at a given time is examined. Computation of integrated water vapor content based on solar radiometer data is discussed.

Calculations to account for the effects of gaseous absorption in the near infrared spectral bands of a solar radiometer are outlined. Such corrections will facilitate calibration of these spectral bands.

In conclusion, the effects of the uncertainties in the current determination of crucial atmospheric parameters on radiance at the satellite level are examined.

Barbara G. Grant, 1989 M.S. Thesis.

"Calibration of the advanced very high resolution radiometer"

Abstract:

This thesis describes the first calibration of the Advanced Very High Resolution Radiometer (AVHRR) on the NOAA-11 satellite. Two methods were used to perform the calibration. Both methods relied on calibrated data from a high resolution sensor that passed over the target site at the White Sands Missile Range, New Mexico, on November 21, 1988. The first approach required ground reflectance and atmospheric optical depth data taken during overpass time. The second method relied on historical ground reflectance data and utilized standard atmospheric models. The calibration gains varied widely depending on which set of calibration offsets were used, but the agreement between the gains computed by the two methods was very close; approximately 1% in channel 1 and 2% in channel 2. This close agreement indicates that Method 2, which does not require the complexity and expense of field work, could be a viable option for future calibration efforts.

Nadine C. Lu (now Chrien), 1989 M.S. Thesis.

"Radiometric sensitivity comparisons of multispectral imaging systems"

Abstract:

Multispectral imaging systems provide much of the basic data used by the land and ocean civilian remote sensing community. There are numerous multispectral imaging systems which have been and are being developed. A common way to compare the radiometric performance of these sensors is to examine their noise equivalent change in reflectance, $NE\Delta\rho$. The $NE\Delta\rho$ of a sensor is the reflectance difference that is equal to the noise in the recorded signal. This thesis compares the noise equivalent change in reflectance of seven different multispectral imaging systems (AVHRR, AVIRIS, ETM, HIRIS, MODIS-N, SPOT-1 HRV, and TM) for a set of three atmospheric conditions (continental aerosol with 23 km visibility, continental aerosol with 5 km visibility, and a Rayleigh atmosphere), five values of ground reflectance (0.01, 0.10, 0.25, 0.50, and 1.00), a nadir viewing angle, and a solar zenith angle of forty-five degrees.

Mark W. Smith, 1989 M.S. Thesis.

"Effect of infrared reflectance on stem temperatures of Saguaro"

Abstract:

The role of high infrared (IR) reflectance in the temperature regulation of a single species of cactus, *Cereus giganteus* (saguaro cactus), was investigated.

Two independent methods were used to determine the effect of high near-IR reflectance on *C. giganteus* stem temperatures. The first method was to measure the surface temperature of two individual plants of comparable size and health, one of which was partially shaded by a canopy of loose sun-screening material. The second method involved the numerical solution on a computer of the energy balance, or heat transfer, equation for *C. giganteus*.

High reflectance at near-IR wavelengths was found to decrease the peak surface temperature reached by *C. giganteus* by 3.2 to 3.3° C. This figure is valid for the fairly mild environmental conditions encountered in the Sonoran Desert at a altitude of 940 m during late September and early October.

Stuart F. Biggar, 1990 Ph.D. dissertation.

"In-flight methods for satellite sensor absolute radiometric calibration"

Abstract:

Three methods for the in-flight absolute radiometric calibration of satellite sensors are presented. The Thematic Mapper (TM) on the Landsat series satellite and the HRV on the SPOT satellite have been calibrated using the three methods at the White Sands Missile Range in New Mexico. Ground and airborne measurements of ground reflectance, radiance, and atmospheric and weather parameters are made coincident with satellite image acquisition. The data are analyzed to determine the appropriate inputs to radiative transfer and other codes. The codes compute the radiance at the satellite sensor entrance pupil which is then compared to the average digital count from the sensor viewing the measured ground area. The three methods are the reflectance-based, radiance-based, and irradiance-based methods.

The relevant parts of the theory of radiative transfer through an atmosphere are reviewed. The partition of measurements of extinction optical depth into Rayleigh, aerosol and absorption optical depths is discussed. The reflectance-based method is described along with the assumptions made. The reflectance-based method accuracy is no better than the measurement of the ground reflectance which is made in reference to a standard of spectral reflectance.

The radiance-based method is described. The underlying standard for the radiance method is a standard of spectral irradiance used to calibrate a radiometer. The calibration of a radiometer to make radiance measurements is discussed along with the use of radiative transfer computations to correct for the residual atmosphere above the radiometer measurements.

The irradiance-based method is described. It uses the measurement of the downward direct and total irradiance at the ground level to determine the apparent reflectance seen by a sensor. This method uses an analytic approximation to compute the reflectance without the use of an "exact" radiative transfer code. The direct-to-total irradiance ratio implicitly gives the description of the scattering normally calculated from the size distribution and the assumption of Mie scattering by the aerosols.

The three methods give independent results which should allow for the detection of possible systematic errors in any of the three methods. In fact, all three methods give results which are within the estimated errors of each method on most calibration dates. We expect, therefore, that the results of our sensor calibrations are within 5 percent of the actual value.

Quinn J. Hart, 1990 M.S. Thesis.

"Surface and aerosol models for use in radiative transfer codes"

Abstract:

Absolute radiometric calibrations of Landsat 5 Thematic Mapper satellite are improved with the inclusion of a method to invert optical depth measurements to obtain an aerosol particle size distribution and a non-lambertian surface reflectance model. Also, a program is developed to improve speed and standardization of the entire calibration procedure.

The inverted size distributions can predict radiances varying from the previous Jungian distributions by as much as 5 percent, though an improvement on the estimated error does not improve by the same percent.

An empirical model for the surface reflection of White Sands using a two-degree polynomial fit as a function of scattering angle was employed. The model reduced estimated errors in radiance predictions by up to one percent.

Satellite calibrations dating from October, 1984 are reprocessed using the improved methods and a linear estimation of satellite counts per unit radiance versus time since launch is determined.

Carmen T. Guzman, 1991 M.S. Thesis.

"Ratioing Radiometer, solar diffuser system for in-flight calibration of multispectral satellite sensors"

Abstract:

One promising way to calibrate a satellite sensor in flight is to place a sun-illuminated white diffuser panel in front of it. However, even if the panel is only deployed for brief periods, it may degrade in the space environment. A ratioing radiometer to monitor the panel changes is described and an error analysis associated with the use of the radiometer is presented.

The procedures used to test the optical properties of different candidate panel materials are described. Results of spectral directional-hemispherical reflectance, bidirectional reflectance, polarization and depolarization measurements are presented for nine panel candidate materials before and after exposure to proton and ultraviolet radiation.

In this preliminary evaluation it was found that, although polytetrafluoroethylene materials exhibited the most desirable characteristics before proton and UV irradiation, IITRI paint, YB-71 withstood proton and UV irradiation the best and is the choice among the nine materials tested.

Iain R. Penny, 1991 M.S. Thesis.

"Detector-based absolute radiometric calibration of lamps and reflectance panels"

Abstract:

The absolute calibration of remote sensing systems is based upon radiometric standards. The irradiance standards are currently 1000-watt quartz tungsten-halogen lamps that are traced to National Institute of Standards and Technology standards by a middle party at a significant cost. Lamp instability, short lifetime and calibration inaccuracy present problems.

A detector-based absolute calibration technique is described here to replace the lamp calibration in the visible portion of the spectrum (approximately 400 to 700 nm). The system utilizes a quantum efficient QED-200 trap detector in an automated facility to absolutely characterize lamp spectral irradiances or reflectance panel spectral radiances.

The measured irradiance of a directly-viewed standard lamp compared favorably (within 0.8%) to the original calibration. Standard-reflectance-panel radiance measurements could not be accurately compared (within 5%) to the illuminating standard lamp irradiance because of excessive stray light in the calibration facility.

Mark W. Smith, 1992 Ph.D. Dissertation.

"Design, construction, and calibration of a portable short wave infrared Spectrometer"

Abstract:

This dissertation describes the design, construction, and calibration of a portable short wave infrared (SWIR) spectroradiometer. The main use for the instrument is the collection of ground reflectance and radiance data for the radiometric calibration of operational and proposed high spectral resolution remote-sensing systems, such as the Airborne Visible and Infrared Imaging Spectrometer (AVIRIS), the Moderate Resolution Imaging Spectrometer (MODIS), the High Resolution Imaging Spectrometer (HIRIS), and the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER). The instrument will also be used for cross calibrating Earth Observing System (EOS) calibration facilities and for a variety of high spectral resolution studies in earth science. The instrument is designed to be carried as a backpack unit, on a vehicle, or in a helicopter or airplane. The spectroradiometer covers the range from 1.05 to 2.45 μm . The

spectral sampling interval is 2.37 nm and the spectral resolution is variable from about 5 nm to more than 100 nm. A single spectrum can be acquired in as little as 1 s. The signal-to-noise ratio (SNR for a single 1-s scan is about 90 at a wavelength of 2.2 μm for a Lambertian surface of 100% reflectance illuminated by the sun at normal incidence with 14-nm spectral resolution, a 25° background temperature, and no atmospheric attenuation. The SNR can be improved by averaging multiple scans. Field-of-view defining optics are coupled by a flexible fiber optics bundle to the spectroradiometer, which consists of a non-scanning concave holographic diffraction grating with flat local field imaged onto a 1024-element liquid-nitrogen-cooled PtSi linear-array detector. The combination of concave grating and linear-array detector was chosen in preference to Fourier transform, Hadamard transform, and scanned grating monochromator systems on the basis of simplicity, high SNR, and greatest radiometric accuracy.

Carter Lee Grotbeck, 1995 Ph.D. Dissertation.

"Solar aureole instrumentation and inversion techniques for aerosol studies"

Abstract:

The in-flight calibration of satellite radiometers using ground truth measurements relies on the use of an atmospheric radiative transfer code. The accuracy of the calibration depends largely on the aerosol model used in the radiative transfer code. In order to improve the calibrations, a camera system has been developed for the determination of the aerosol size distribution, index of refraction, and scattering phase function. In addition, the camera can be used to measure ozone and water vapor content. The camera uses a two dimensional silicon CCD array to image the sun and the solar aureole. A filter wheel provides sixteen spectral bands from 380 nm to 1045 nm. The camera is mounted on an altitude-azimuth mount for tracking the sun. An external computer allows automatic or manual data acquisition. The aerosol size distribution retrieval is based on the combined inversion of solar extinction and solar aureole data. The real part of the aerosol refractive index is determined using scattering measurements in the near-backward direction, while diffuse-to-global measurements provide the imaginary part. The performance of the inversion schemes is illustrated to simulated in-flight satellite signal predictions over both high and low reflectance targets.

Concluding remarks

This grant enabled the Remote Sensing Group to continue its work on vicarious calibration (VC), started under the sponsorship of NASA for Thematic Mapper and CNES for SPOT/HRV. Without it, the accuracy and dependability of VC would be unknown and VC would not be in a position to provide invaluable independent calibrations of EOS and other sensors. Only through such independent calibrations can we be assured that the uncertainty of the results provided by the on-board calibrators are not corrupted by systematic errors. This is simply because the radiance-based and reflectance-based VC methods have been validated and they themselves are independent, relying in one case primarily on an irradiance standard and in the other on a standard of diffuse reflectance. VC can also provide the important link between different sensors whether they be located on the same platform, such as ASTER, MISR and MODIS, or of different generations such as MODIS AM and MODIS PM.

Other activities which were facilitated by the support provided by the grant are:

- the study of materials for use as solar diffusers

- the radiometric, mechanical, and electronic conceptual design of a ratioing radiometer to monitor the radiance stability of a solar diffuser

- a study to determine the response sensitivity of a narrow-band filter radiometer to filter shifts in the presence of solar Fraunhofer lines.

And perhaps the most significant achievement has been the graduation of 13 students supported, or partially supported by the grant, or the equipment procured by the grant. Several of these have gone on to work on EOS-related projects, notably: Stuart F. Biggar (Research Associate Professor in the RSG at the Optical Sciences Center working on ASTER and MODIS calibration), Carol J. Bruegge (Calibration Scientist for MISR at JPL), Nadine Lu Chrien (Algorithm developer and data analyst for MISR at JPL), Ronald G. Holmes (Program element manager for calibration of TES at JPL), and Mark W. Smith (Scientist working for MOPITT at NCAR).

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Magdeleine Dinguirard, on leave from CERT (under CNES contract) in Toulouse

Nianzeng Che, on leave from the People's Republic of China

Richard P. Santer, on leave from the University of Lille, now at the Universit é du Littoral

Philippe M. Teillet, on leave from the Canada Centre for Remote Sensing

Benfan Yuan, on leave from the People's Republic of China

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